中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

BESIII

粒子自旋和宇称量子数的测量

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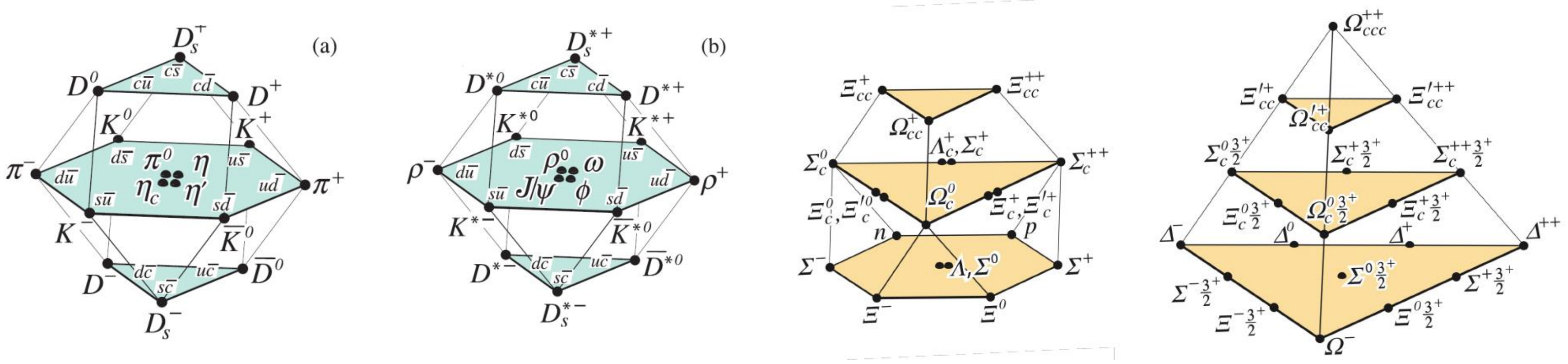
第二届强子物理新发展研讨会 暨 强子物理在线论坛100期特别活动，
合肥，中国科学技术大学，30 June 2024 to 4 July 2024

常规强子和奇异态物质

- ✓ Conventional hadrons: meson $|q\bar{q}\rangle$, baryon: $|qqq\rangle$ or $|\bar{q}\bar{q}\bar{q}\rangle$



- ✓ Conventional Spin-parity quantum numbers

Mesons: $n^{2S+1}L_J$, $P = (-1)^{L+1}$; $\exists C, C = (-1)^{L+S}$

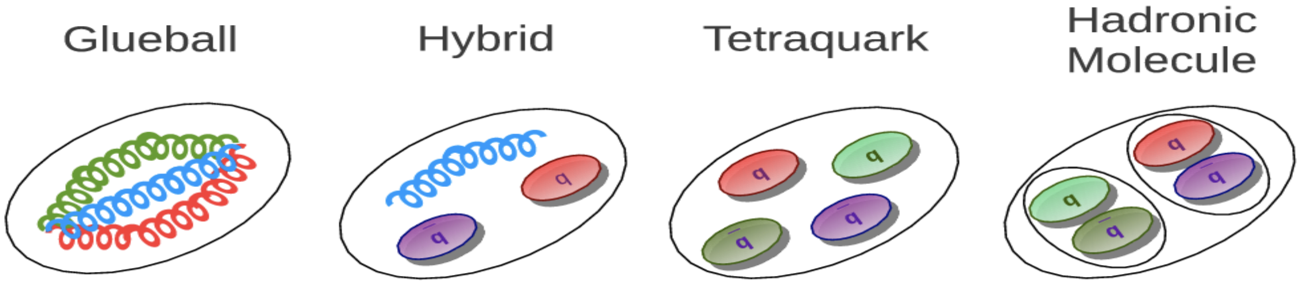
e.g. $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, 2^{--}, \ldots$

常规强子和奇特态物质

- ✓ Conventional Spin-parity quantum numbers (continued)

  Baryons: classified by $(D,\ L_N^P), e.g.\ N=0$: nucleon and Δ, $P=+$
  or classified by $|X^{2S+1}\ L_\pi\ J^P|$ with $\mathrm{X=N,\Delta,\ldots}$, $\pi=$
  $M\ or\ A$ **(symmetry)**

- ✓ QCD allows for "exotics"

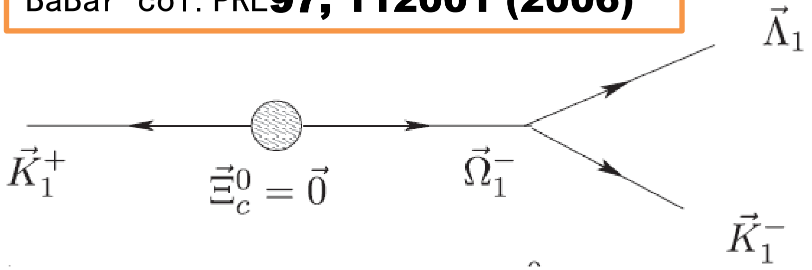


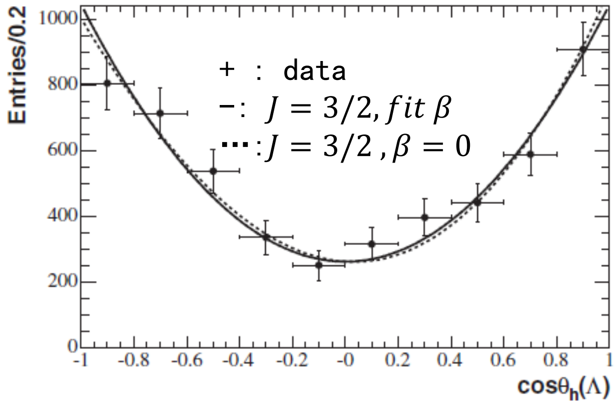
Exotic quantum numbers: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

自旋-宇称量子数的测量方法

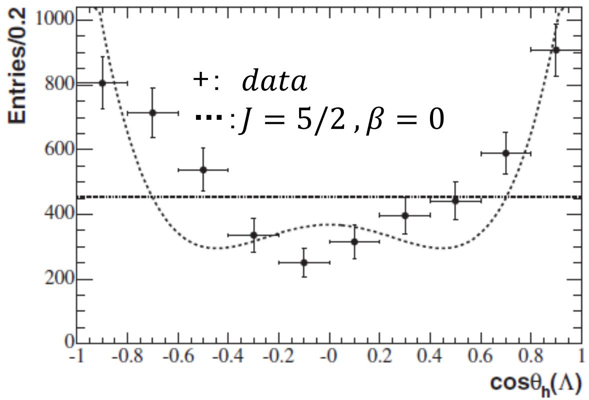
- ✓ Angular distribution analysis: Ω^-,: $J^P = 3/2^+$

BaBar col. PRL **97, 112001 (2006)**



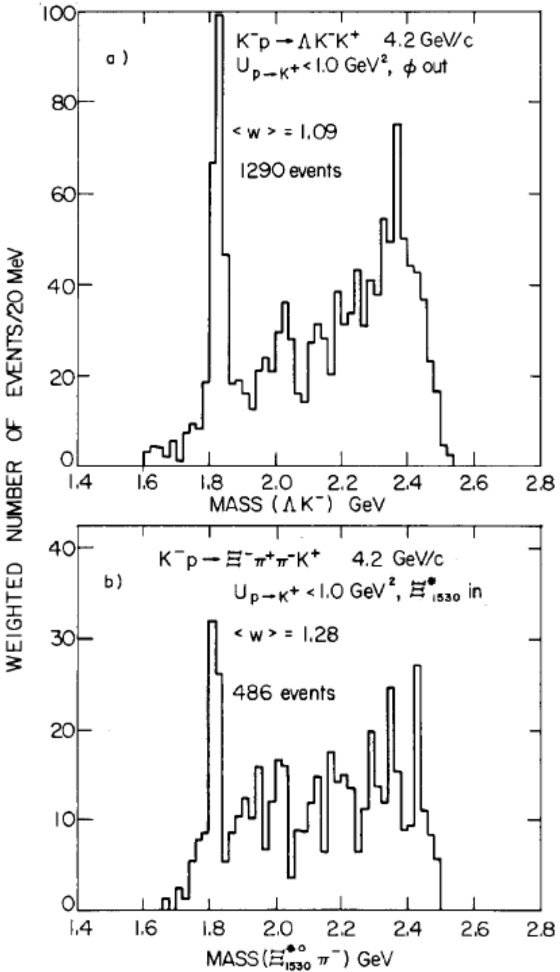


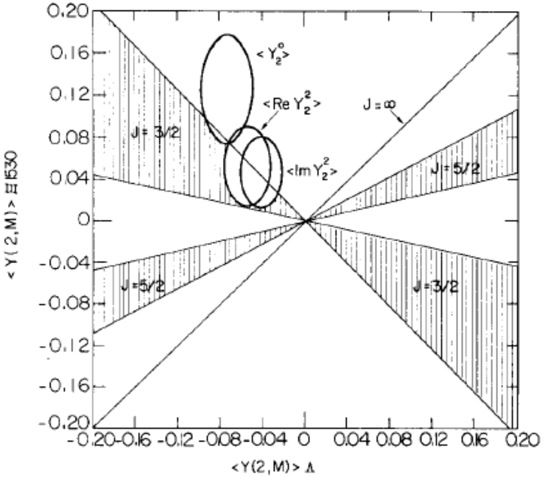
- ✓ $$\frac{dN}{d\cos\theta_h} \propto \begin{cases} 1+\beta\cos\theta_h & (J=1/2) \\ 1+3\cos^2\theta_h+\beta\cos\theta_h(5-9\cos^2\theta_h) & (J=3/2) \\ 1-2\cos^2\theta_h+5\cos^4\theta_h+\beta\cos\theta_h * \\ (5-26\cos^2\theta_h+25\cos^4\theta_h) & (J=5/2) \end{cases}$$

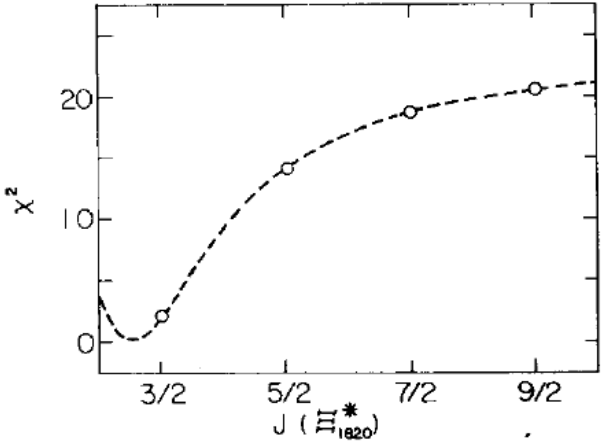


- ✓ χ^2 test

✓ Moment analysis: $\Xi(1820)$: $J = 3/2$ Phys.Lett., 77B, 451







- ✓ @4.2GeV : $K^-p \to \Lambda K^+K^-, \Xi^-K^+\pi^+\pi^-$
  - ➢ $\Xi^{*-} \to \Lambda K^-$
  - ➢ $\Xi^{*-} \to \Xi^{*0}(1530)\pi^-$

Moment relation:

- ✓ $\langle Y_L^M \rangle_{\Xi^{*-}(1530)} = \left[1 - \frac{2L(L+1)(1-\gamma')}{(2J+3)(2J-1)}\right] \langle Y_L^M \rangle_\Lambda$

- ✓ Data: CERN K^- beam to 2m hydrogen bubble chamber

Λ_c自旋宇称量子数的测量

✓ PDG 2018

Λ_c^+ $I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗∗

The parity of the Λ_c^+ is defined to be positive (as are the parities of the proton, neutron, and Λ). The quark content is $u\,d\,c$. Results of an analysis of $pK^-\pi^+$ decays (JEZABEK 92) are consistent with $J = 1/2$. Nobody doubts that the spin is indeed 1/2.

We have omitted some results that have been superseded by later experiments. The omitted results may be found in earlier editions.

✓ PDG 2022

Λ_c^+ $I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗∗

The parity of the Λ_c^+ is defined to be positive (as are the parities of the proton, neutron, and Λ). The quark content is $u\,d\,c$. Results of an analysis of $pK^-\pi^+$ decays (JEZABEK 92) are consistent with $J = 1/2$. ABLIKIM 21N determines the Λ_c^+ spin to be $J = 1/2$, from an angular analysis of various 2-body Λ_c^+ decays in $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$.

We have omitted some results that have been superseded by later experiments. The omitted results may be found in earlier editions.

1. M. Ablikim et al. (BESIII Collaboration), Phys. Rev., D103, L091101 (2021);

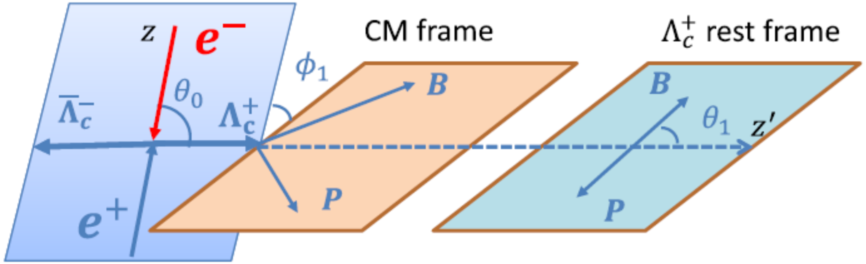
- $587\ \mathrm{pb}^{-1}$ at $\sqrt{s} = 4.6$ GeV
- likelihood test using angular distribution for $e^+e^- \to \Lambda_c\overline{\Lambda}_c$, $\Lambda_c \to pK_S^0, \Lambda\pi^+, \Sigma^0\pi^+$, and $\Sigma^+\pi^0$.
- Tow spin hypotheses, $J = \frac{1}{2}, \frac{3}{2}$ are tested.
- likelihood function:

$$\mathcal{L}_i^J(N^i) = \prod_{k=1}^{N^i} \frac{1}{C^i} \mathcal{W}^J(\theta_0^k, \theta_1^k, \phi_1^k, \ldots, \theta_n^k, \phi_n^k),$$

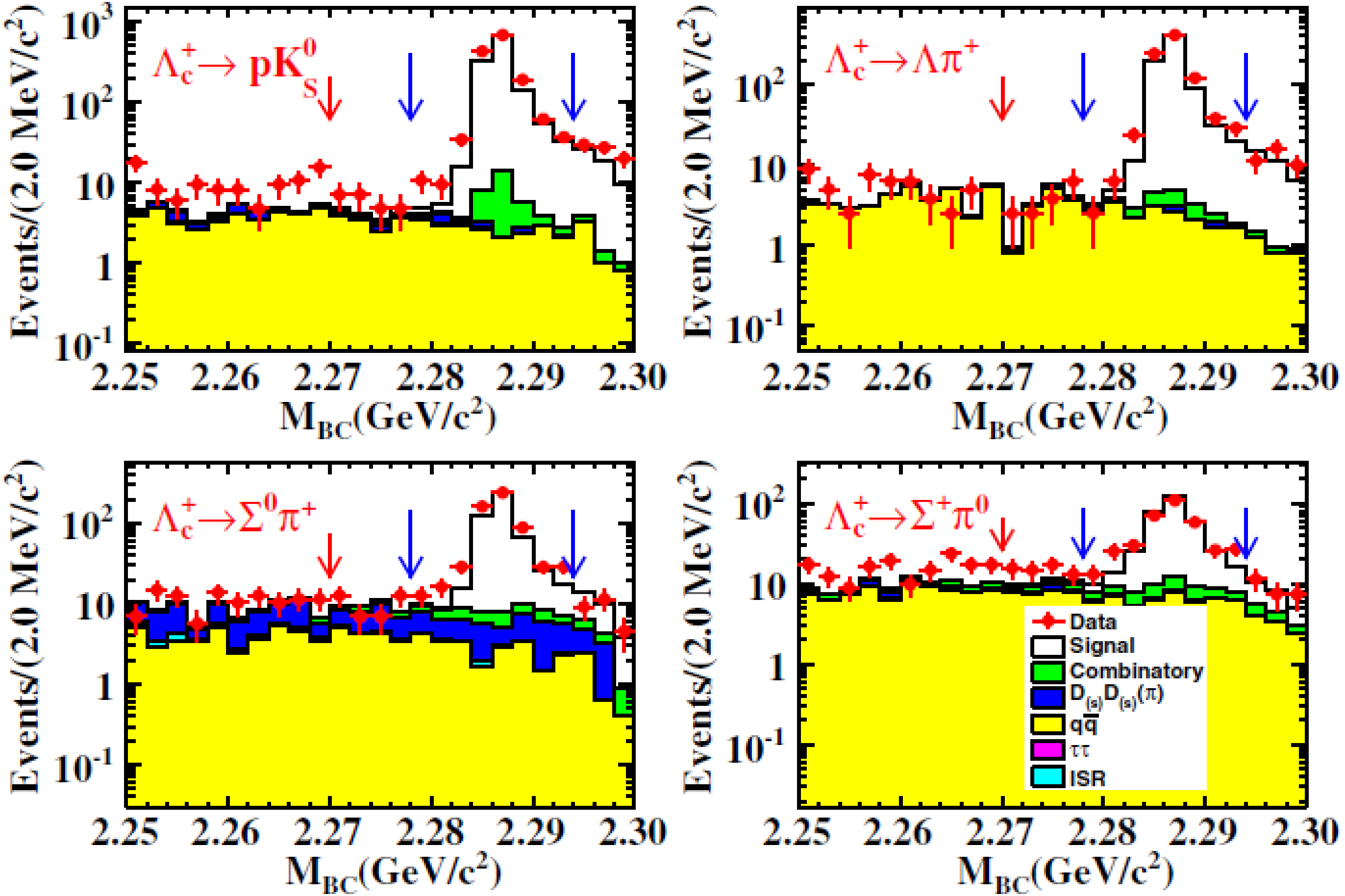
- Angular distribution:

$$\mathcal{W}^{J=\frac{1}{2}}(\theta_0, \theta_1, \phi_1) \propto 1 + \alpha\cos^2\theta_0 + \mathcal{P}_\mathcal{T} \sin\theta_1 \sin\phi_1,$$

$$\text{with} \quad \mathcal{P}_\mathcal{T} = \alpha_{[pK_S^0]} \sqrt{1-\alpha^2} \cos\theta_0 \sin\theta_0 \sin\xi,$$



- Survived events: 2829 events, 242 bkg. events

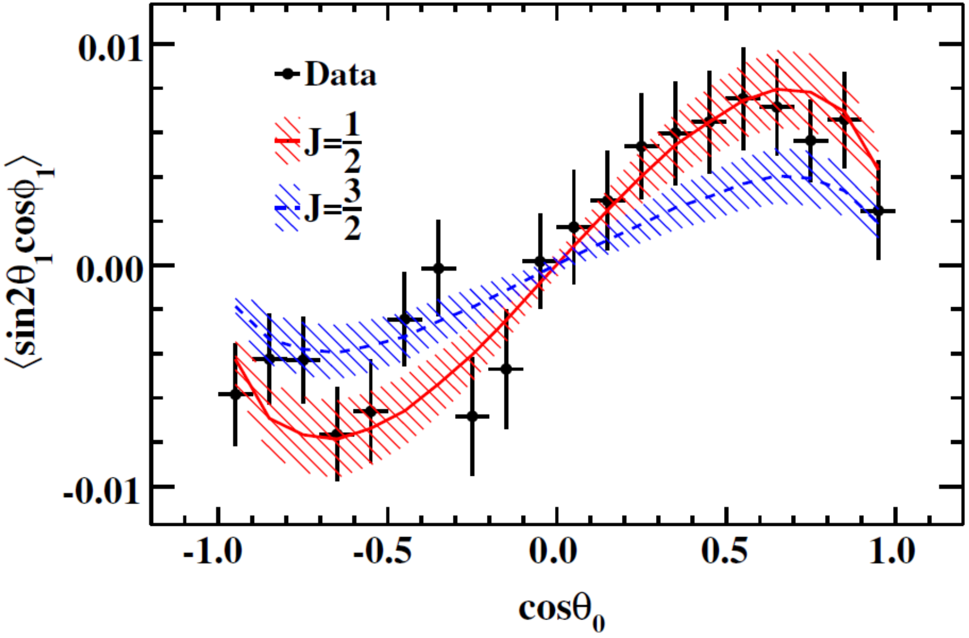


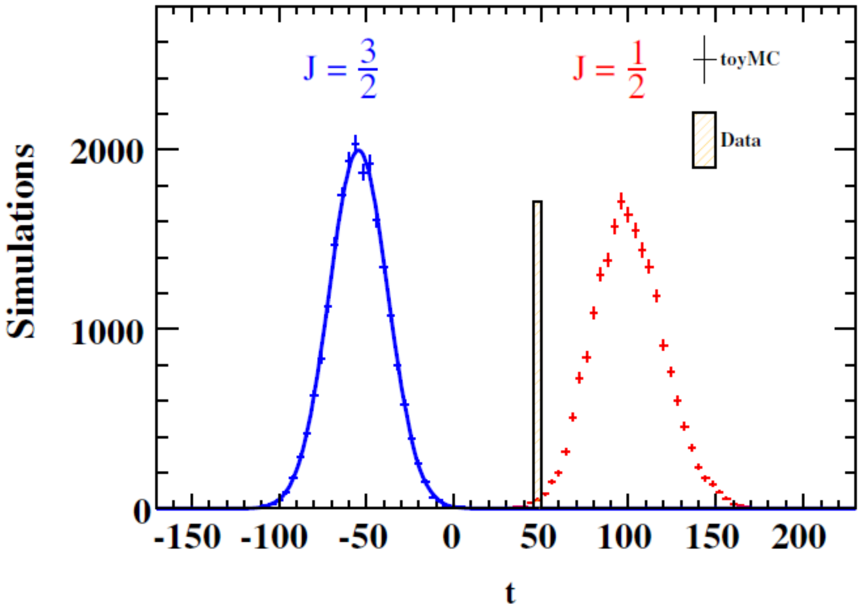
✓ $-\ln \sum L_i = -45.2 \ \left(J = \frac{1}{2}\right),$

$= -21.5 \ \left(J = \frac{3}{2}\right)$

✓ $t = -2\ln(L^{3/2}/L^{1/2})$

✓ 6σ significance for spin $J = 1/2$ over $3/2$





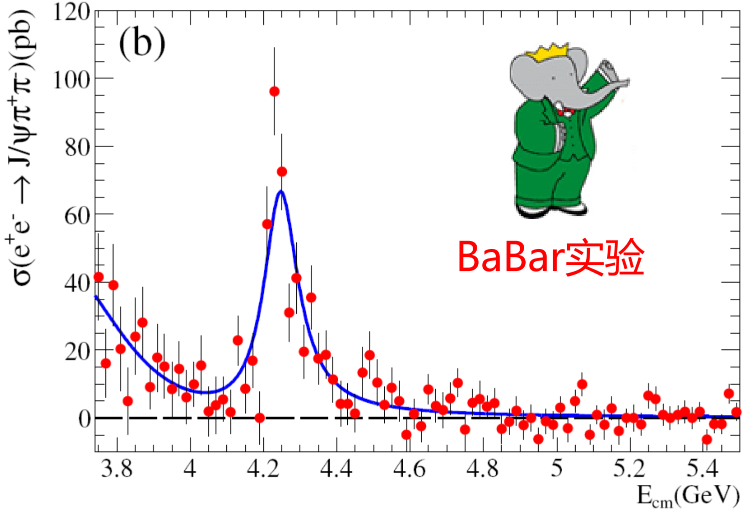
$Z_c(3900)$自旋和宇称的测量

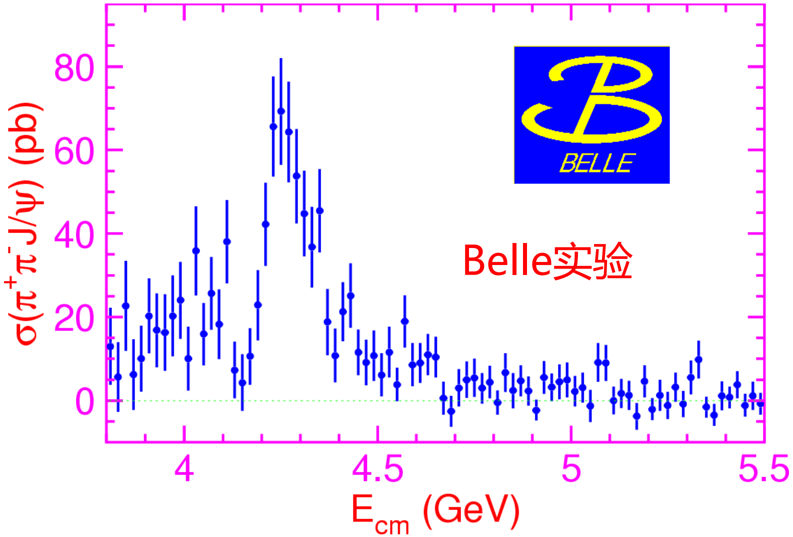
$Z_c(3900)$ $I^G(J^{PC}) = 1^+(1^{+-})$

$Z_c(3900)$ MASS	3887.1 ± 2.6 MeV (S = 1.7)
$Z_c(3900)$ WIDTH	28.4 ± 2.6 MeV

1. Ablikim, M. et.al, (BESIII) Phys.Rev.Lett.,110, 252001 (2013).
2. Ablikim, M. et.al, (BESIII), Phys.Rev.Lett.,119, 072001 (2017).

$e^+e^- \to \pi^+\pi^- J/\psi$ 事例

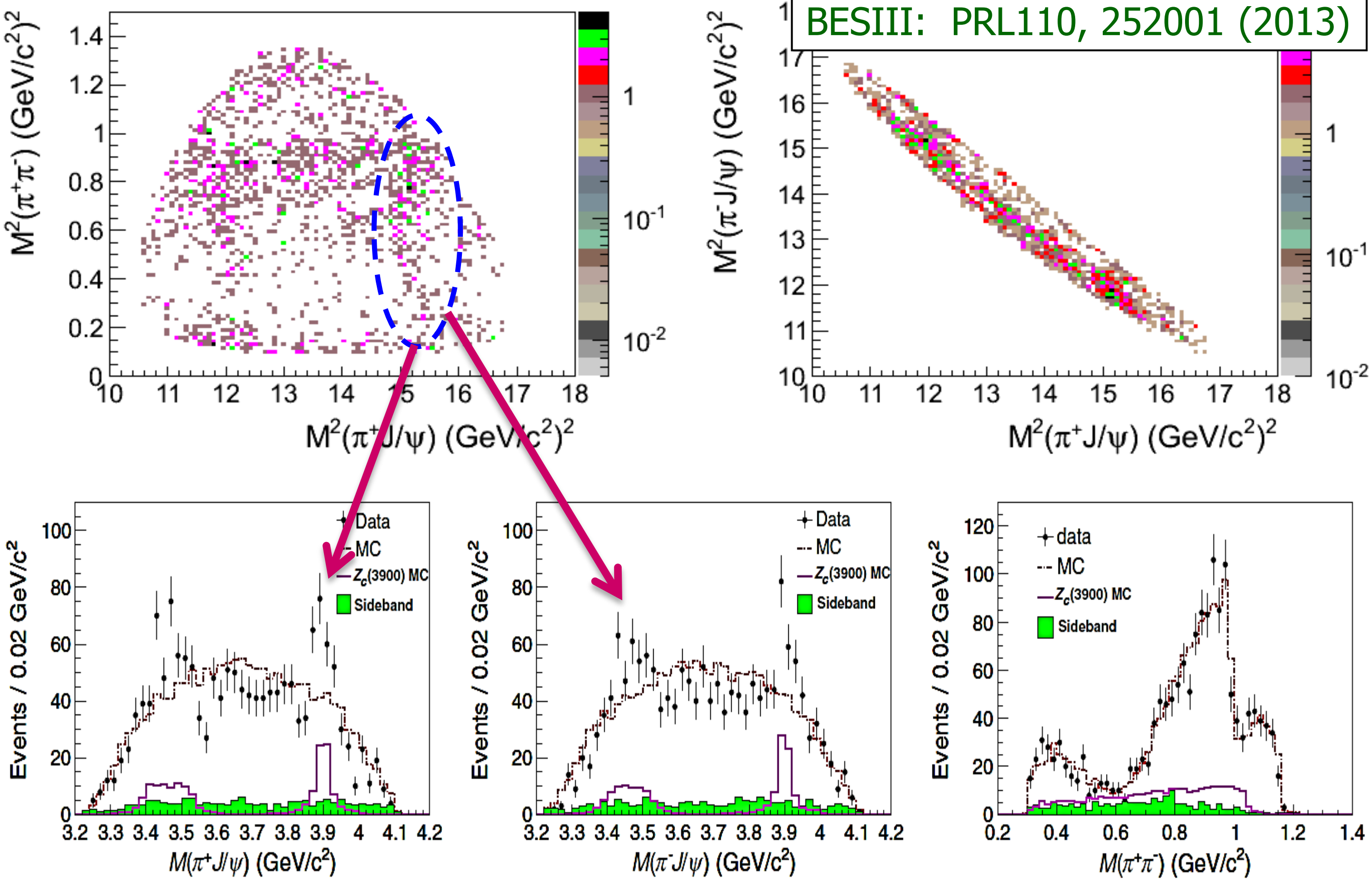




- ✓ $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ ~ 4.26 GeV 截面最大
- ✓ 建议在4.26GeV采集45 天数据，可积累500 pb^{-1} 数据
- ✓ 在30天内积累了 525 pb^{-1} !是 CLEO-c 数据的40倍!

Dalitz plot and mass spectrum

BESIII: PRL110, 252001 (2013)

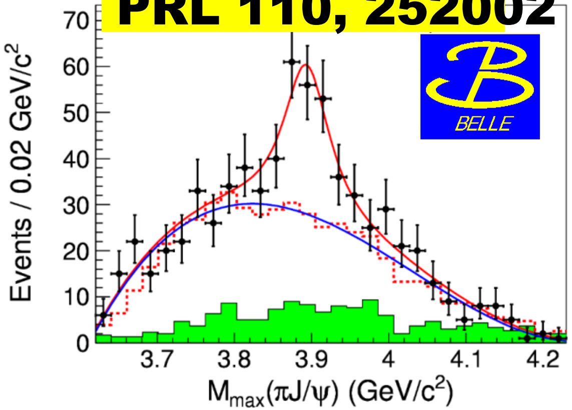


$Z_c(3900)$ confirmed by other experiments

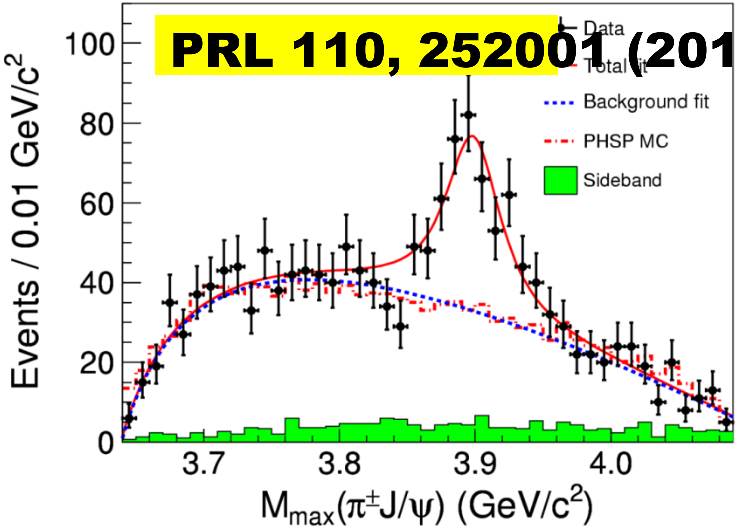
BESIII : Mar. 24, 2013
Belle : Mar. 30, 2013
CLEOc : Apr. 10, 2013

Z_c established !

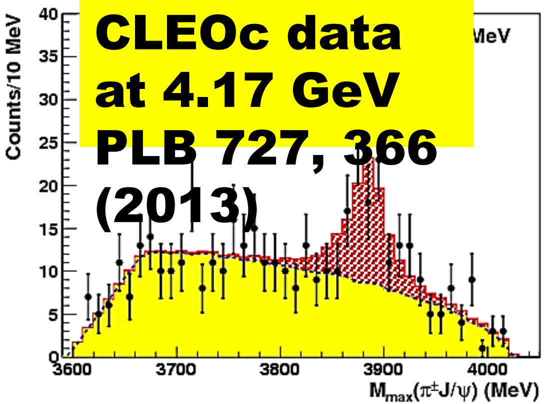
PRL 110, 252002 (2013)



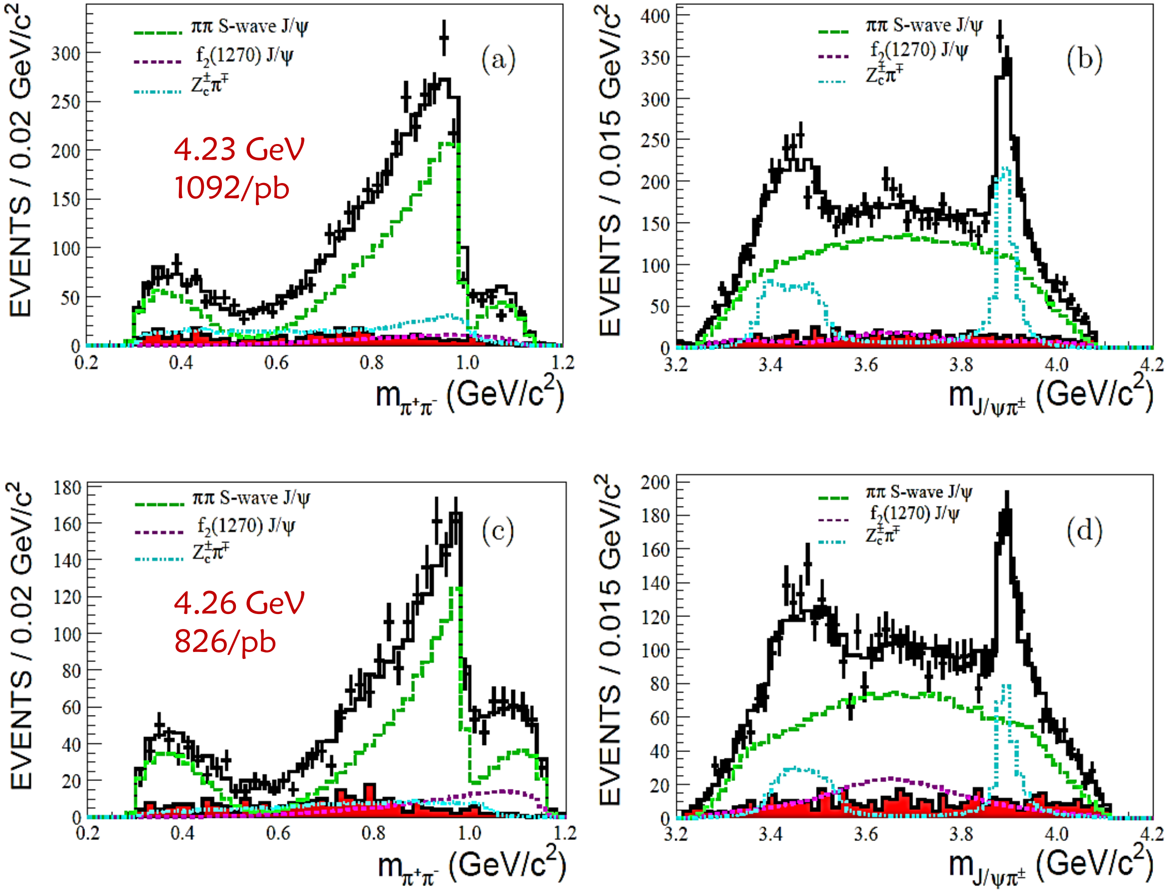
PRL 110, 252001 (2013)



CLEOc data at 4.17 GeV
PLB 727, 366 (2013)



Spin and parity measurement

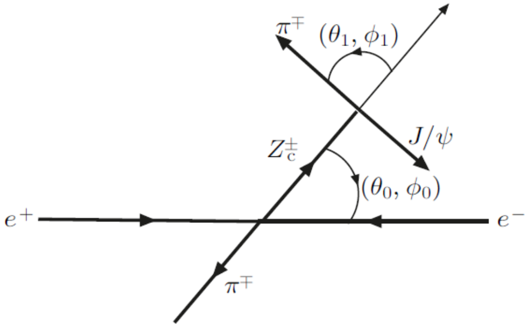


- ✓ simultaneous fit of two data sets
- ✓ helicity amplitude for $e^+e^- \to \gamma^* \to R(\pi\pi)\psi$ & $Z_c\psi, \psi \to l^+l^-$
- ✓ **Isobar model:** $\sigma\ f_0, f_0(1370), (1270), Z_c^{\pm}$
- ✓ $Z_c^{\pm}$ as 1^+ state

✓ $Z_c(3900)$ 自旋宇称的角分布分析

1. $e^+e^- \to \pi^\pm Z_c^\mp$

$$\frac{dN}{d\cos\theta_0} \propto \begin{cases} \sin^2\theta_0 & (J^p = 0^-) \\ 1+\alpha_0\cos^2\theta_0 & (J^P = 1^+) \\ 1+\cos^2\theta_0 & (J^P = 1^-) \\ 1+\alpha_0\cos^2\theta_0 & (J^P = 2^-) \\ 1+\cos^2\theta_0 & (J^P = 2^+) \end{cases}$$

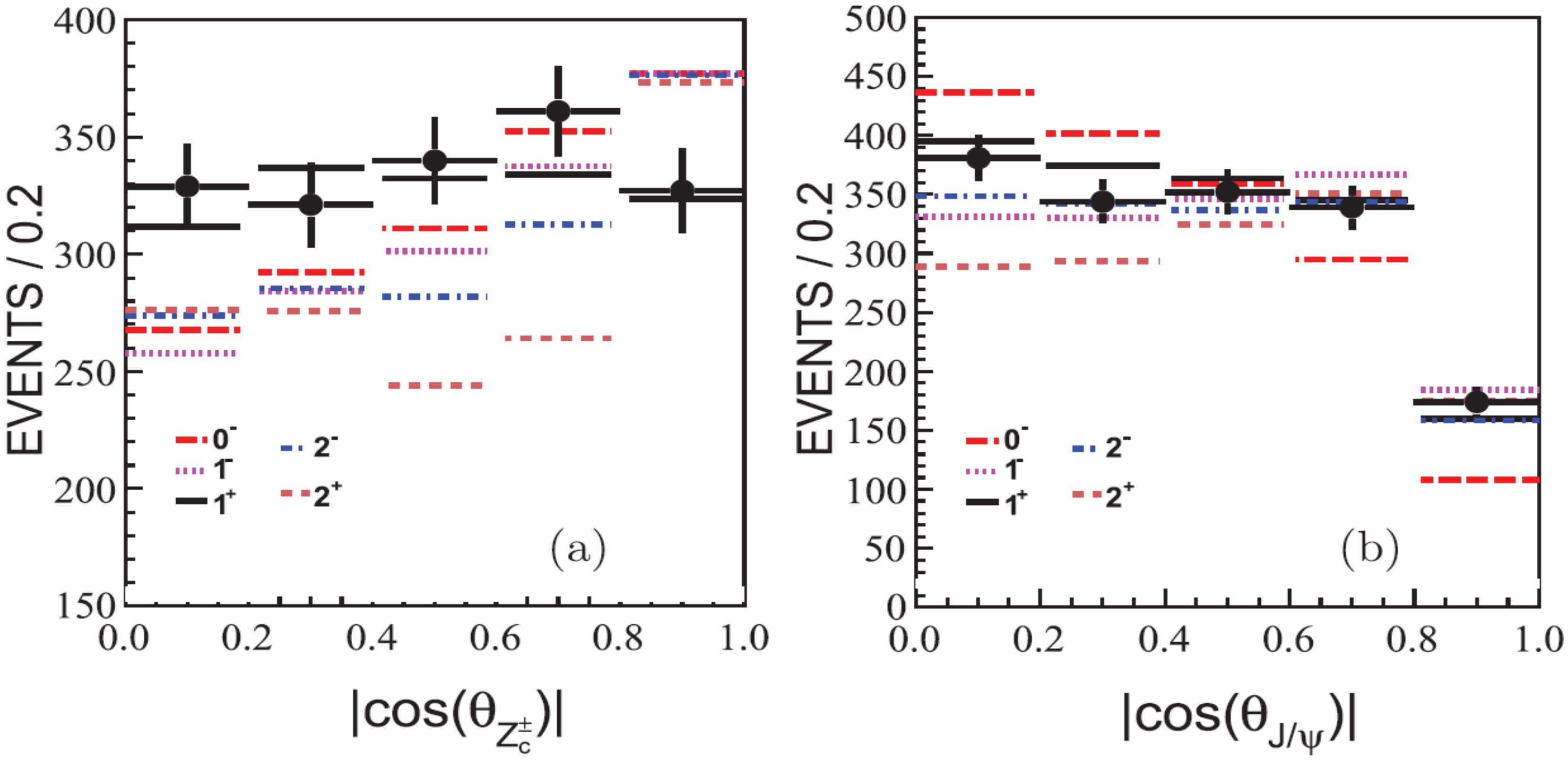


Ref. Chin. Phys. Lett. Vol. 33, 061401 (2016)

2. $Z_c^\mp \to \pi^\mp J/\psi$

$$\frac{dN}{d\cos\theta_1} \propto \begin{cases} 1 & (J^p = 0^-) \\ 1+\alpha_1\cos^2\theta_1 & (J^P = 1^+) \\ 1+\cos^2\theta_1 & (J^P = 1^-) \\ 1+\alpha_1\cos^2\theta_1+\alpha_2\cos^4\theta_1 & (J^P = 2^-) \\ 1-3\cos^2\theta_1+4\cos^4\theta_1 & (J^P = 2^+) \end{cases}$$

✓ $Z_c(3900)$ 自旋宇称的角分布检验和统计显著性



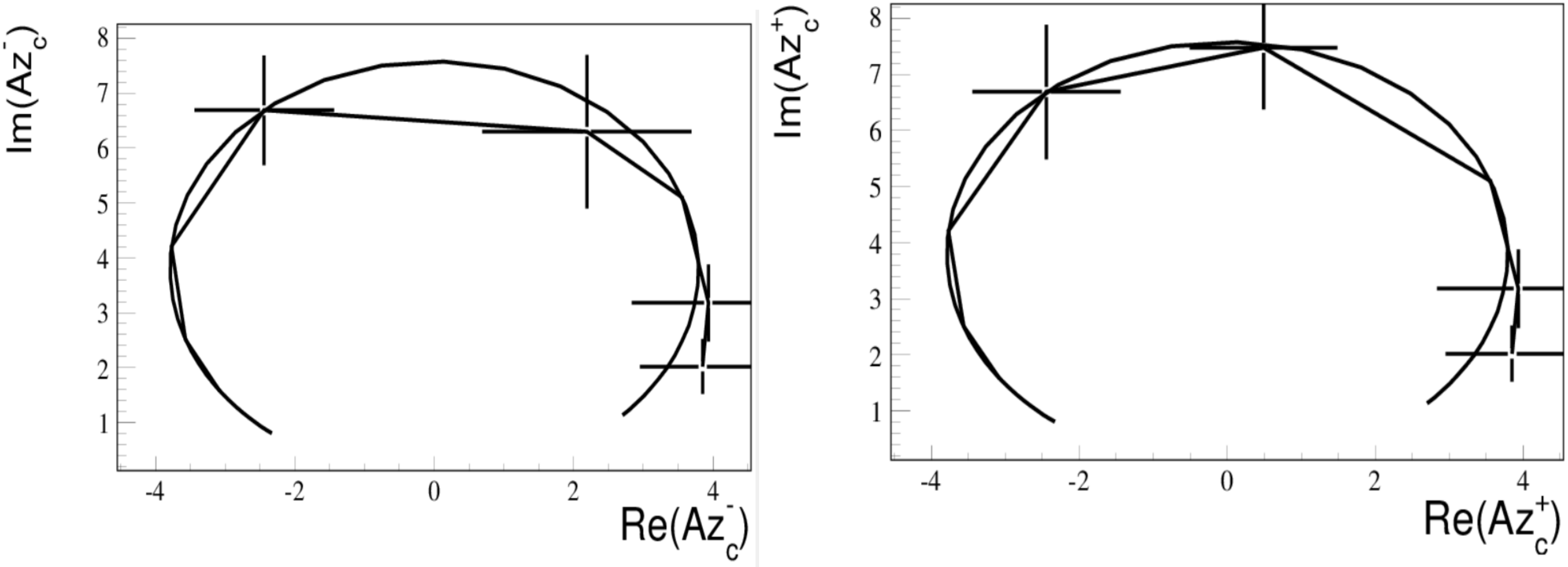
✓ $Z_c(3900)$ 统计显著性

- H_0 hypothesis: $J^P = 1^+$; H_1 hypothesis: $J^P = 0^-$ or $(1^-, 2\hat{}\pm)$;
- Statistics: $t \equiv -2\ln\lambda = 2[\ln L_{\max}(H_1) - \ln L_{\max}(H_0)],$
- p-value : $p(t_{\rm obs}) = \int_{t_{\rm obs}}^{\infty} \chi^2(t;r)dt.$
- Significance

$$\int_{-S}^{S} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx = 1 - p(t_{\rm obs}) = \int_0^{t_{\rm obs}} \chi^2(t;r)dt.$$

Hypothesis	$\Delta(-2\ln L)$	Δ(ndf)	Significance
1^+ over 0^-	94.0	13	7.6σ
1^+ over 1^-	158.3	13	10.8σ
1^+ over 2^-	151.9	13	10.5σ
1^+ over 2^+	96.0	13	7.7σ

✓ $Z_c^{\pm}$ Argand plot



$X(2085)$自旋和宇称的测量

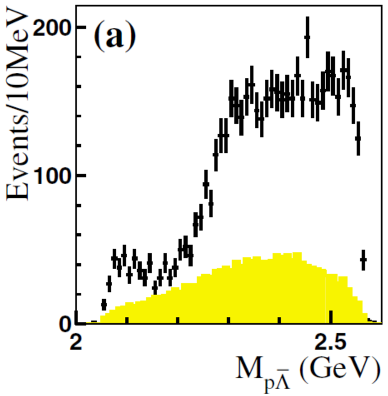
$$e^+e^- \to K^-X(2085)^+, X(2085)^+ \to \bar{p}\Lambda$$

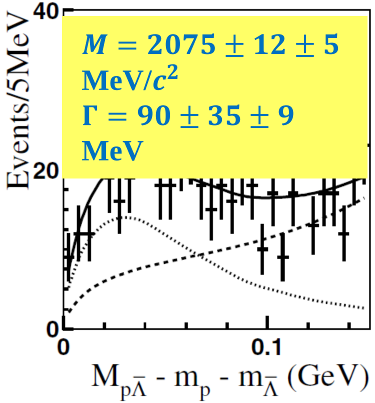
$$M_{\text{pole}} = 2084^{+4}_{-2} \pm 9\ \text{MeV},\ \Gamma = 58^{+4}_{-3} \pm 25\ \ \text{MeV}$$

Ablikim, M., et.al, (BESIII) Phys.Rev.Lett., 131, 151901(2023)

$p\bar{\Lambda}$ threshold enhancement $X(2085)$

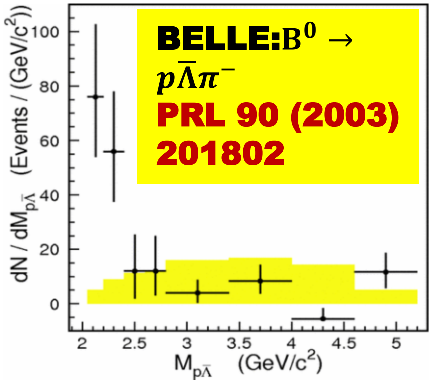
BESII: $J/\psi \to pK^{-}\bar{\Lambda} + c.c.$
PRL 93 (2004) 112002

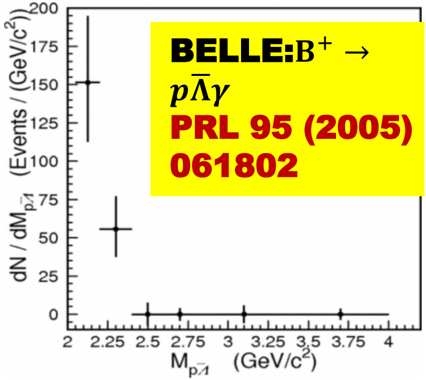


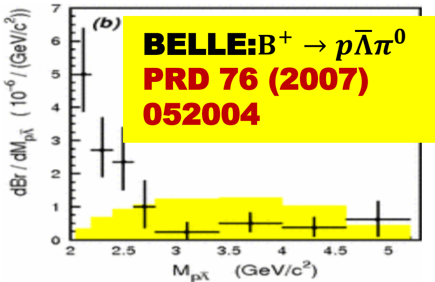


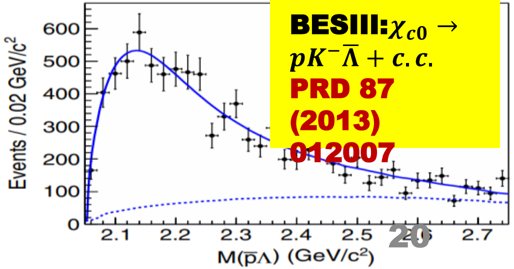
Motivation

- Observed at BESII in 2004
- Similar structure was seen in several B meson and charmonium decays
- Investigated theoretically under scenario of quark model, FSI and chiral effective theory



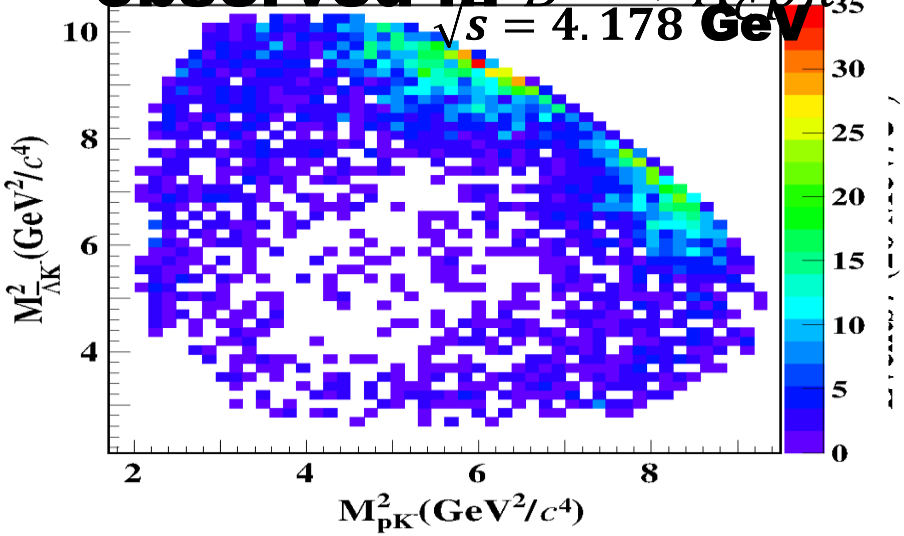




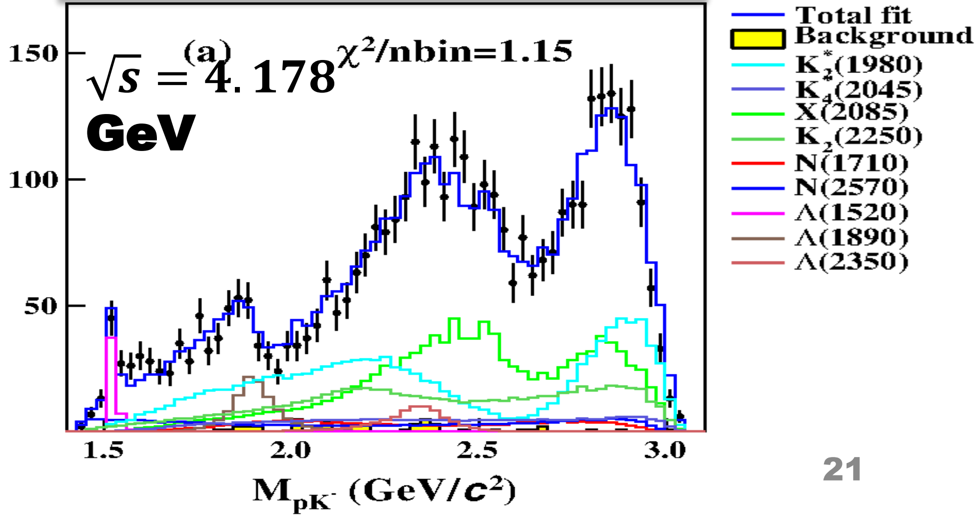


$X(2085)$ in $e^+e^- \to \gamma^* \to pK^-\bar{\Lambda}$+c.c.

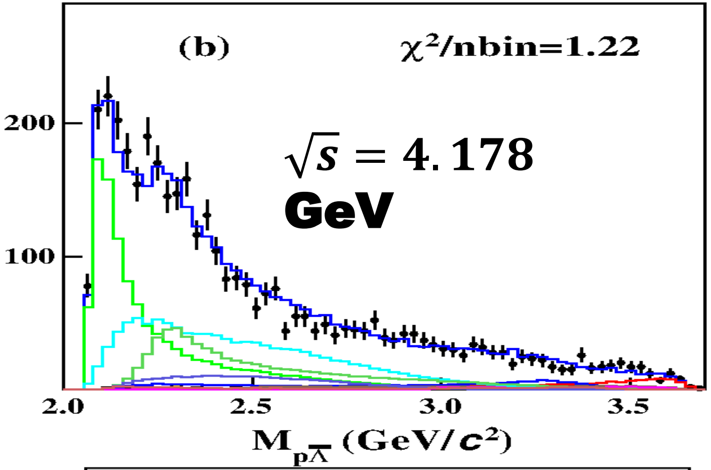
- $X(2085)$[**K(2085)**] **first observed in** $J/\psi \to pK^-\Lambda + c.c.$**, but spin-parity not measured.**
- **Similar evidence found in** $B \to p\Lambda\pi$, **and** $\psi', \chi_{cJ} \to pK^-\Lambda$.
- **Near** $p\Lambda_c$ **threshold, an enhancement also observed in** $B^- \to \Lambda_c^+ \bar{p}\pi^-$

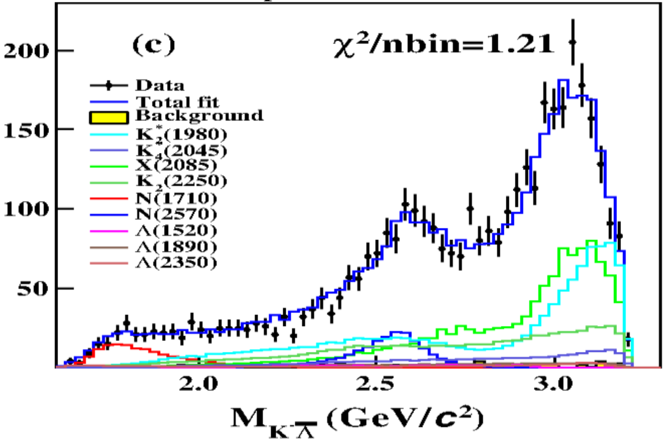


PRL**131, 151901 (2023)**



$X(2085)$ in $e^+e^- \to \gamma^* \to pK^-\bar{\Lambda}$ + c.c.



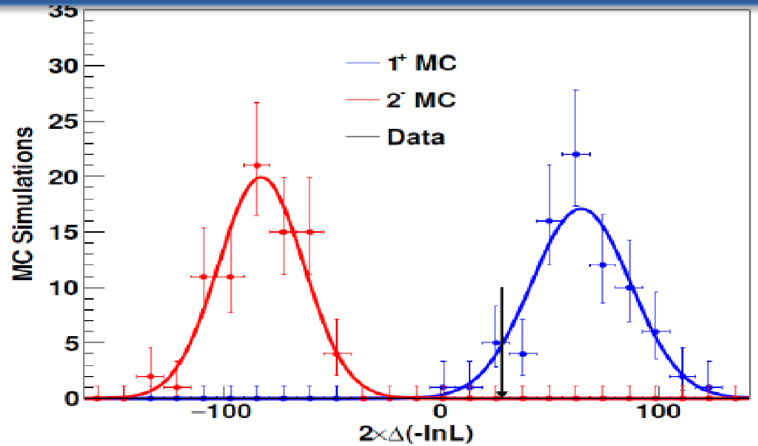


- $X(2085)$, $J^P = 1^+$
- $M_{pole} = (2084^{+4}_{-2} \pm 9)$ **MeV**
- $\Gamma_{pole} = (58^{+4}_{-3} \pm 25)$ **MeV**

	$\Delta \ln \mathcal{L}$	Δndf	Significance
1^+ over 0^-	40.6	4	8.3
1^+ over 1^-	30.2	2	7.5
1^+ over 2^+	44.8	2	9.2
1^+ over 2^-	13.8	0	5.3

$\sqrt{s}$ (GeV)	M_{pole} (MeV/c^2)	Γ_{pole} (MeV)
4.008	2085±14	50±16
4.178	2085±6	62±10
4.226	2088±10	68±12
4.258	2083±11	48±10
4.416	2088±13	56±12
4.682	2092±10	54±10
Average	2086±4	56±5

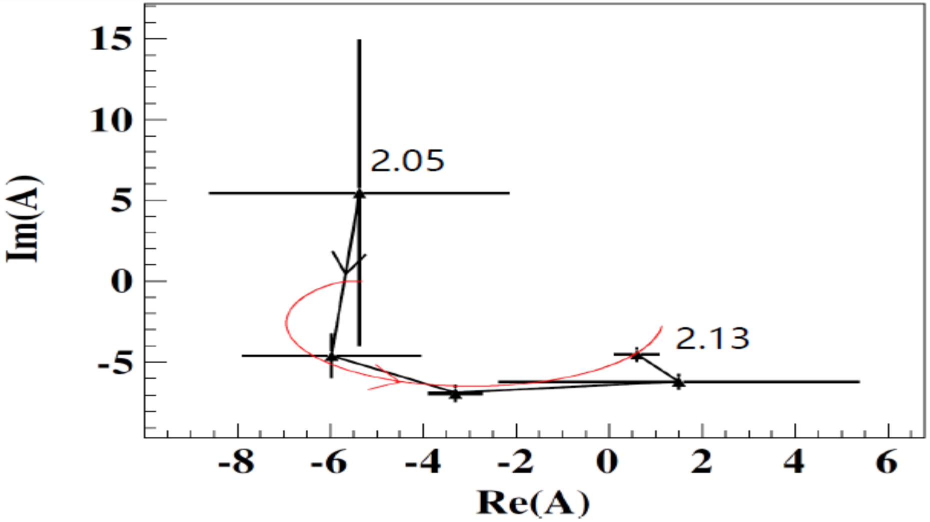
Check significance with toy MC method



	$\Delta \ln \mathcal{L}$	Δndf	Significance
1^+ over 0^-	40.6	4	8.3
1^+ over 1^-	30.2	2	7.5
1^+ over 2^+	44.8	2	9.2
1^+ over 2^-	13.8	0	5.3

- ✓ The statistical significances of 1^+ over 0^-, 1^-, and 2^+ are obtained with $\Delta \ln L = \ln L^{1^+} - \ln L^{J^P}$ and Δndf
- ✓ For 1^+ over 2^-, the Δndf is assumed to be 1, following PRL 115 (2015), 072001.
- ✓ The approach based on MC simulation is checked. The $t = -2\ln(L^{2^-}/L^{1^+})$ distribution suggests a statistical significance $5.6\,\sigma$

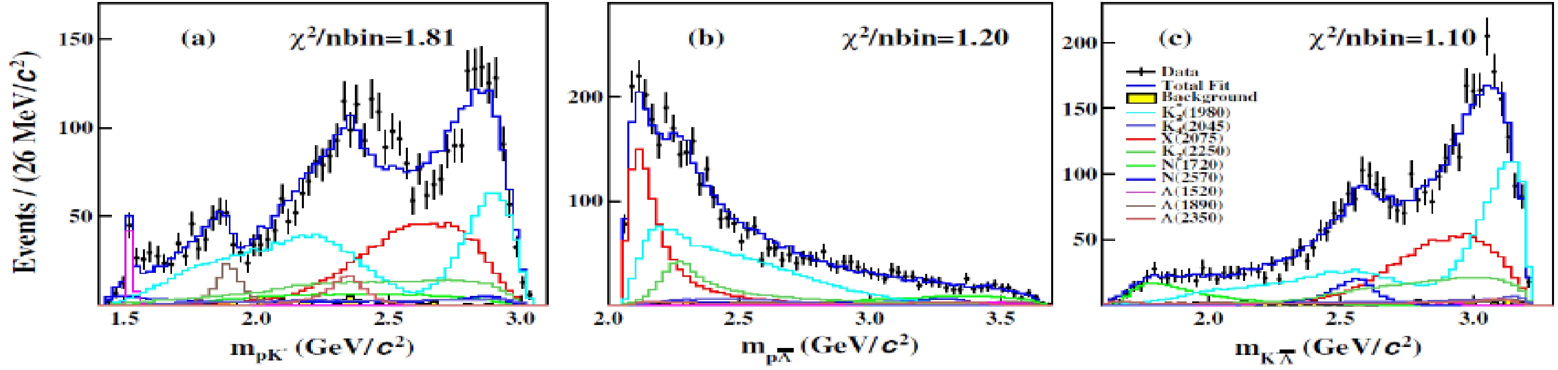
X(2085) Argand plot



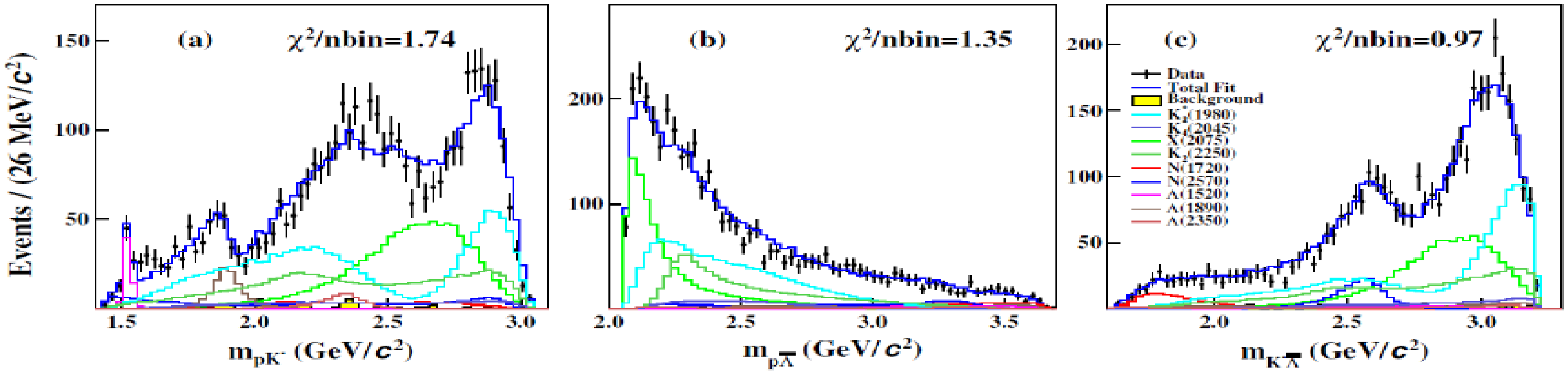
- From 2.05 – 2.13 GeV with step size 20 MeV
- BW function replaced with a complex number A_i in point i
- Cubic interpolation between two points
- No conclusion whether $X(2075)$ exhibits the characteristics of a resonance or not.

check alternative J^P

$J^P = 0^-$



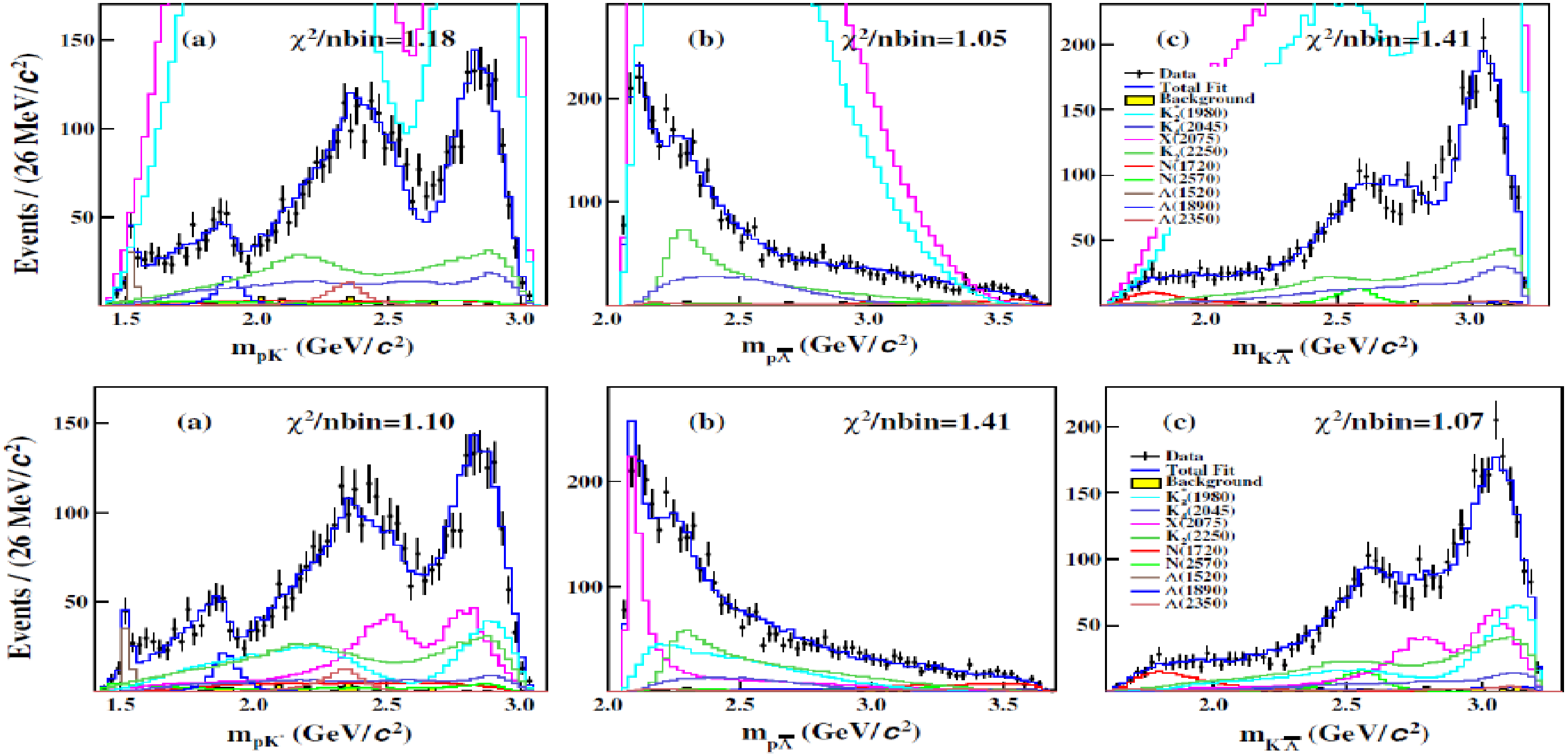
$J^P = 1^-$



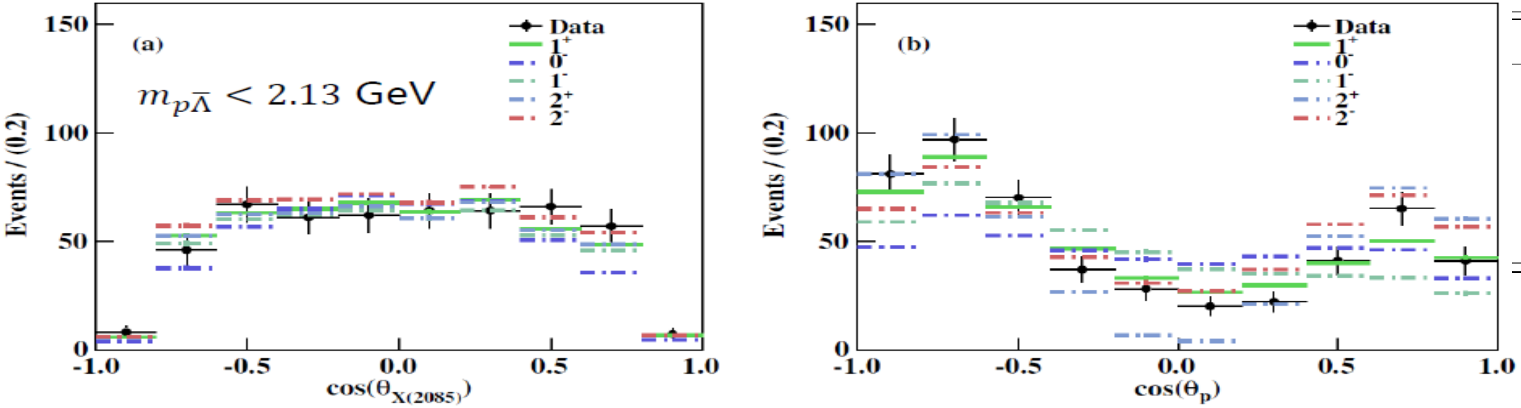
check alternative J^P

$J^P = 2^+$

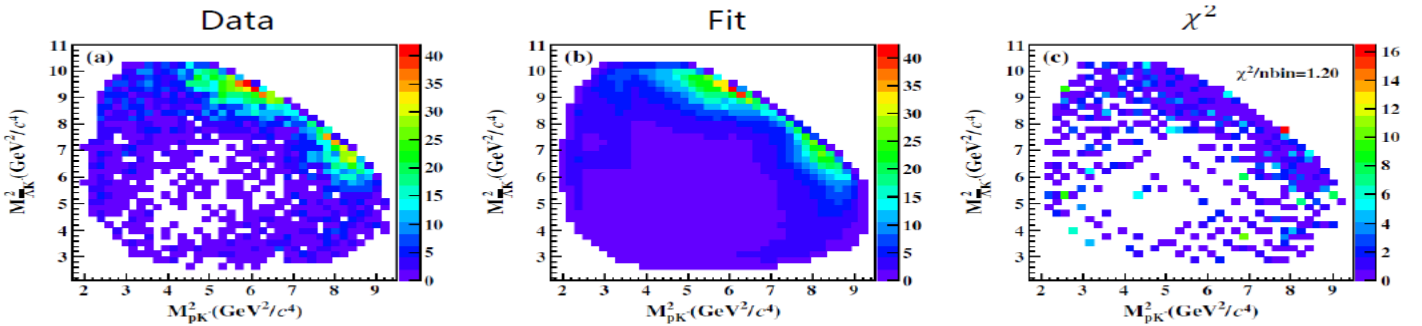
$J^P = 2^-$



Data favor 1^+ hypothesis

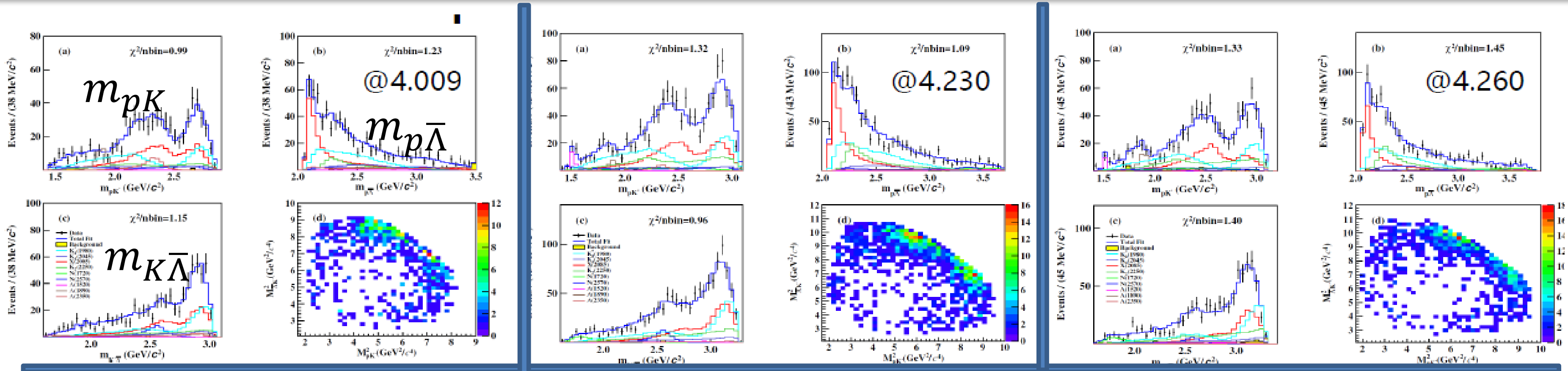


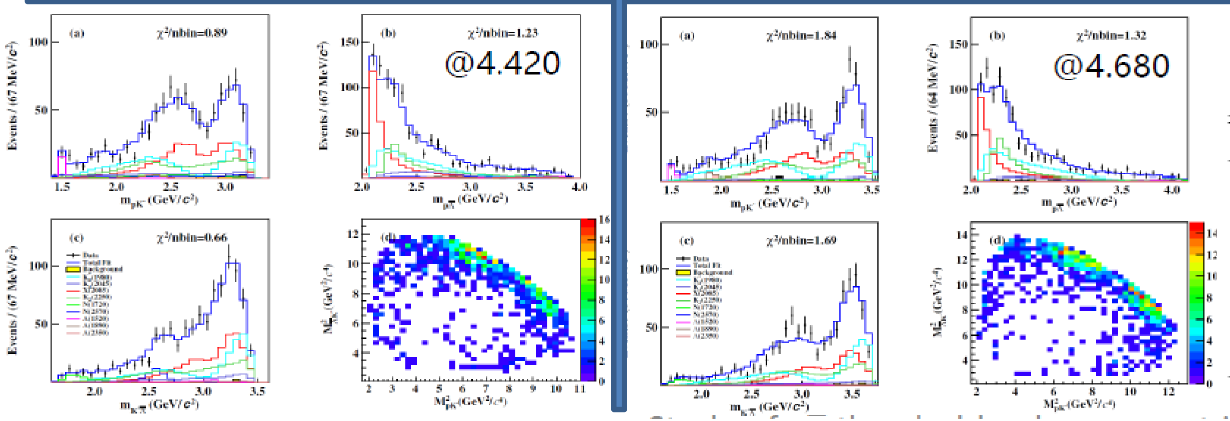
J^P	$\chi^2_{\mathrm{angle}}/\mathrm{nbin}$
1^+	19.4/20
0^-	107.2/20
1^-	80.4/20
2^+	53.2/20
2^-	41.2/20



J^P	$\chi^2_{\mathrm{Dalitz}}/\mathrm{nbin}$
1^+	490.5/409
0^-	602.7/409
1^-	632.1/409
2^+	549.1/409
2^-	502.7/409

Data at other five points





Data luminosity

$\sqrt{s}$	$\mathcal{L}_{\rm int}$	Year
4.008	482.0 ± 4.7	2011
4.178	3189.0 ± 31.9	2016
4.226	1100.9 ± 7.0	2013
4.258	828.4 ± 5.5	2013
4.416	1090.7 ± 7.2	2014
4.682	1669.3 ± 9.0	2020

其他自旋-宇称量子数测量的范例

1. M. Ablikim et al. (BESIII Collaboration), Observation of an Isoscalar Resonance with Exotic $J^{PC}=1^{-+}$ Quantum Numbers in in $J/\psi \to \gamma\eta\eta'$, Phys.Rev.Lett. 129, 192002 (2022);
2. M. Ablikim et al. (BESIII Collaboration), companion paper, Phys. Rev. D 106, 072012 (2022).

3. M. Ablikim, et.al., (BESIII) , Model-Independent Determination of the Spin of the Ω^- and Its Polarization Alignment in $\psi(2S) \to \Omega^-\bar{\Omega}^+$, Phys. Rev. Lett. 126 (2021) 9, 092002.

4. M. Ablikim , et.al., (BESIII), Determination of spin and parity of $D^{*(s)}$ mesons, Phys. Lett., B846, 138245(2023)

Summary

- **Spin-parity measurements using hypothesis testing**
- **Distinguishing spin parity through angular distribution, angular moment analysis, and fit quality**
- **Exotic spin-parity measurements as a tool for identifying exotic states.**

Thanks for your attention!

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